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In the event of a levee failure (due to any initiating event) winds blowing over the length of the flooded island would generate waves that have the potential to erode the inner slope (inboard side) of the levee, which are not armored. Inboard levee erosion could cause secondary levee breaches to form.

This section presents an analysis of wind and the corresponding wind waves to use in erosion and risk calculations. A complete description of the wind and wave analysis, including the datasets that were used, and the methodology and results of the analysis is presented in detail in the Wind-Wave Hazard Technical Memorandum (TM) (URS/JBA 2008g).

8.1 INTRODUCTION

As described in Section 4, wind waves pose a potential hazard to Delta levees. In the risk analysis wind-waves are recognized as a potential hazard, but are not evaluated as an independent initiating event that leads to levee failure (see Sections 4.4.4 to 4.4.6). Wind waves and their effects are considered in conjunction with other initiating events that result in levee failure and island flooding. Waves generated on flooded islands lead to erosion of the interior, unprotected slopes of levees, and may cause secondary breaches. Erosion of levee interiors adds to the cost and timing of levee repairs and island recovery, which could be significant in the case of a multiple island levee failure event.

This section describes the analysis of wind and wind-waves in the Delta. The results of this analysis were used as input to the levee erosion model described in Section 10 and used in the levee emergency response and repair analysis (see the discussion in Sections 4 and 10).

To evaluate the wind and wind-wave hazards in the Delta, wind data were collected from multiple locations in and around the Delta region. The wind data were analyzed to estimate the probability of extreme winds and their patterns, seasonal wind occurrences, and a range of wave conditions that may be caused by these winds. A complete description of the wind and wind-wave analysis is given in the Wind-Wave Hazard TM (URS/JBA 2008g).

Although wind setup, wave transmission past levees due to wave overtopping, and the joint probability of high winds/wind waves and high water levels (residuals or storm surges) can be important in the analysis of wind-wave generation, they were considered secondary in regard to their effect on the risk analysis, so were not included. The primary use of the wave data to the risk analysis is in the estimate of the cost of emergency response. The processes just named are not primary drivers in determining those costs.

8.2 METHOD

Winds and wind-waves were analyzed separately. The wind analysis addresses both extreme winds that occur infrequently and typical winds that on average occur throughout each year and season. Extreme winds were analyzed using a probabilistic model of extreme wind events that models the temporal and spatial patterns of winds across the Delta and Suisun Marsh region. For typical winds, the percent occurrence of wind speeds was analyzed in multiple directions (wind roses) for two seasons (fall-winter and spring-summer) and multiple locations (identified later).

The approach to the wind-wave portion of the analysis is deterministic rather than probabilistic. Wind-wave height, period, power, and runup were estimated for a range of wind speeds and open-water fetch lengths. Deep water wave conditions were assumed and wave transformations were not addressed in this analysis. A discussion on the validity of the deep-water assumption is provided in the Wind-Wave Hazard TM (URS/JBA 2008g). When the water is too shallow for deep water conditions to apply, wave energy is partially dissipated by bottom friction; therefore, for a given wind speed, wave heights and periods would be less than in deep water. Thus, assuming deep water wave heights and periods for shallow water conditions provide a conservative estimate of wind-wave conditions (USACE 2006).

8.2.1 Extreme Wind Analysis Method

Wind data for the Delta and surrounding region are available from National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS), the California Department of Water Resources (DWR), and the California Irrigation Management Information System (CIMIS). Wind stations are shown on Figure 8-1 and available wind data are summarized in Table 8-1. Only a few wind stations are actually located in the Delta and Suisun Marsh and these stations are located on the periphery (see Figure 8-1).

Agencies that collect wind data use different data collection and quality control procedures. Gaps in wind data were assessed as part of this analysis and are described in the Wind-Wave Hazard TM (URS/JBA 2008g). The height of the wind gage at each station and the sampling interval over which winds are measured vary by station and agency. The wind speed data were corrected to a 10-meter height and for a 1-minute averaging period using the procedure described in the Coastal Engineering Manual (CEM) (USACE 2003) to give a consistent set of regional wind data.

As described in Section 4, the assessment of the potential for levee failures due to hazards that may affect a large geographic region during a single event (i.e., large earthquake), is an important component of the risk analysis for a spatially distributed system such as the Delta[1]. In this context,, the probabilistic wind analysis considers the occurrence of regional extreme wind events that can occur over the spatial dimensions of the Delta, rather than an evaluation of the probability of extreme winds at a particular location independent of other locations, as typically considered in wind hazard studies. Therefore, wind data and synoptic charts were analyzed in terms of regional wind patterns (meteorologies) that cause high winds. These data were obtained from the National Centers for Environmental Prediction (NCEP 2006), North American Regional Reanalysis data, and NOAA Central Library U.S. Daily Weather Maps Project (2006a). The analysis identified three meteorologies that cause high winds:

- **Pacific Low:** an extra-tropical low pressure storm system moving from the Pacific through or to the north of the San Francisco Bay-Delta region, generally causing high winds from the southeast before frontal passage (and also from the southwest to west after frontal passage and sometimes prior to southeast frontal winds) in the Delta.

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[1] At the start of the DRMS study, it was anticipated that a complete spatial and temporal characterization of the wind and wind wave hazard in the Delta would be required in the risk analysis. Later, it was determined this would not be the case. As a result, the full scope of the spatial-temporal wind model was not used in the analysis.

- **Polar Front:** a high pressure cold front extending from the polar region and Canada coupled with a low-pressure system over the southern Great Basin, generally causing high winds from the north in the Delta.
- **Sea Breeze:** thermal pressure gradient between a cold high pressure area over the Pacific and a warm low pressure area inland. Sea breezes generally cause high winds from the west through the straits and over the coastal range and diverge to the northeast and southeast in the Delta.

To model the probability of regional high-wind events, events for each meteorology in the measured regional wind data record were identified. These events were ranked by the highest peak wind speed measured at a wind station. The data generally showed that, during these events, wind speeds were relatively high throughout the Delta and Suisun region. For a given event, regional wind speeds were typically highest at Travis, the site of the former Air Force base. Travis was selected as the reference station to represent the regional probability of extreme wind events. For each meteorology, an extreme value analysis was performed on peak annual wind speeds measured at Travis (i.e., using high wind events only). The analysis resulted in estimates of extreme "meteorological" wind events and their probabilities for Pacific Lows, Polar Fronts, and Sea Breezes.

To evaluate the spatial distribution of wind patterns (speed and direction) throughout the study area, coincident wind data collected at other locations were compared to those collected at Travis. Then, wind data were scaled relative to the Travis data.

Winds were estimated at un-gauged locations throughout the study area by interpolation. For each meteorology, a spatial scaling pattern for wind speed and direction was developed. Using triangulation, wind speeds were interpolated throughout the region for the highest peak wind events measured in each year.

Wind direction for several measured high wind events were interpolated using the Winds on Critical Streamline Surfaces (WOCSS) model (Ludwig et al. 1991). The WOCSS model was also tested for wind speed interpolation, but linear interpolation was selected as a more appropriate scheme. The wind speed and direction fields were interpolated for multiple events to estimate typical (mean) patterns of: (1) (normalized) wind speed and (2) direction.

The normalized wind speed patterns and wind direction patterns developed for the meteorologies were used as the spatial scaling patterns. The variability in these patterns was accounted for in the probabilistic model.

Empirical probability distributions were developed for the direction, duration, and month of occurrence of measured high wind events. These distributions were used to characterize these parameters for extreme wind events.

8.2.2 Wind-Wave Analysis Methods

Simple parametric models for wind-wave generation and wave runup (USACE 1984, 2003; TAW 2002) were used to develop "look-up tables" for wind-wave height, period, power, and runup. Each look-up table is arranged by wind speed and fetch length. The range in wind speed covers seasonal and extreme winds, and the range in fetch lengths covers possible fetches in Delta sloughs and islands and Suisun Marsh. The specifics of wind-wave conditions depend on island shape and fetch orientation, water depth, bed friction, and vegetation. For purposes of this analysis, site-specific assessments to delineate fetches, estimate water depths, or characterize bed and vegetation types were not performed. The look-up tables developed as part of this analysis are based on deep water conditions to represent Delta sloughs and flooded islands. Because shallow water (relative to the wave length) limits wind-wave growth (USACE 1984, 2003), the use of deep-water waves in the model is conservative.

8.3 EXTREME WIND PROBABILITY MODEL

To model the regional occurrence of extreme wind events, a probabilistic extreme wind probability model (model) was developed. The model was implemented for the Delta and Suisun Marsh region using the collected wind data.

8.3.1 Wind Model Formulation

The wind model for the Delta is given by the following expression:

$$P(S(\underline{x}) > s(\underline{x}), \theta(\underline{x}), d, t \mid m_i) \qquad (8\text{-}1)$$

where

$P(\ )$ = annual probability of exceedance distribution

$\underline{x}$ = vector of geographic locations where the wind is defined

$S(\underline{x})$ = wind speed at location $\underline{x}$

$\theta(\underline{x})$ = wind direction at location $\underline{x}$

d = event duration

t = time of year

m_i = meteorological event type (meteorology)

Equation 8-1 calculates the probability of wind events in the Delta and Suisun Marsh occurring in a direction and duration for a given period of the year. Different meteorologies are assumed to be independent.

Reference wind speed distribution. Given the occurrence of a meteorology m_i, a probability distribution of wind speeds for a reference location, Travis, was determined. This distribution can be expressed:

$$P(S_R > s \mid m_i) \qquad (8\text{-}2)$$

where

S_R = the wind speed at a reference location

Spatial wind speed distribution. An occurrence of a wind event at the Travis reference location will be accompanied by an associated pattern of coincident winds throughout the Delta. These spatial patterns of winds throughout the Delta are spatially correlated because they are associated with the same wind event and meteorology. The coincident wind speeds can be expressed:

$$S(\underline{x}, m_i) = S_R(m_i)\, u(\underline{x}, m_i) \qquad (8\text{-}3)$$

where

$u(\underline{x}, m_i)$ = spatial pattern of normalized wind speeds (with respect to the reference location and wind speed, S_R) in the Delta and Suisun Marsh, and defined as a function of meteorology

Given the occurrence of a wind speed at the reference location, the spatial pattern of wind speed will be random and can be expressed:

$$P(u(\underline{x}, m_i)) \tag{8-4}$$

The distribution of this random variability of the spatial wind speed pattern with respect to the reference station can be modeled by a lognormal distribution. The distribution parameters are:

$\mu(\underline{x}, m_i)$ = the mean of the natural logarithm of the normalized wind speeds at location $\underline{x}$

$\sigma(\underline{x}, m_i)$ = the standard deviation of the natural logarithm of the normalized wind speeds at location $\underline{x}$; the variability of the spatial wind speed pattern is assumed to be perfectly correlated in space

The review of wind speed data at the stations analyzed showed a high degree of correlation of the observed winds in the region[2]. From the perspective of assessing risk, assuming the wind speeds are perfectly correlated over the dimensions of the Delta is conservative.[3]

The lognormal distributions of the spatial wind speed pattern variability are truncated to account for the fact that real wind speed values are limited and may not reach extreme values in the distribution tails. Depending on location, the distributions were truncated to two or three standard deviations ($\pm 2\sigma$ or $\pm 3\sigma$), which spans most of the empirical data distribution. The joint probability distribution of the independent parameters of reference wind speed (S_R) and the spatial wind speed variability (u) was then integrated to get a single-parameter exceedance probability distribution for wind speed at a particular location.

The exceedance probability of wind speeds at locations throughout the Delta (x) is a function of the wind speed at the reference location (SR) and the random variability of the spatial wind speed pattern (u). The combination of these two random variables can be used to derive the probability distribution on wind speed at any location in the Delta and Suisun Marsh:

$$P(S(\underline{x}) > s(\underline{x}) \mid m_i) = P(S_R * u(\underline{x}) > s(\underline{x}) \mid u(x), m_i)\ P(u(\underline{x}) \mid m_i) \tag{8-5}$$

Spatial wind direction distribution. For each meteorology, a probability mass function (PMF) on wind speed direction was determined from observations. This distribution is expressed:

$$P(\theta(\underline{x}) \mid m_i) \tag{8-6}$$

where

$\theta(\underline{x})$ = the wind direction for a given event at location $\underline{x}$.

The spatial pattern of wind directions can be denoted:

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[2] As part of this analysis, a correlation analysis (estimation of the variances and covariances) was not carried out. As a result, the distances over which correlations are very high is not known.

[3] As noted previously, the spatial-temporal probabilistic model of wind speeds was not used in the risk analysis.

$$\theta(\underline{x}, m_i) = h(\underline{x}, m_i) + \eta(\underline{x}_m, m_i) \quad (8\text{-}7)$$

where

$h(\underline{x}, m_i)$ = mean spatial wind direction pattern in the Delta and Suisun Bay, defined as a function of meteorology, m_i

$\eta(\underline{x}_m, m_i)$ = random variability of wind direction relative to the mean spatial wind direction pattern, represented as a PMF at:

$\underline{x}_m$ = the location of the wind station nearest to $\underline{x}$.

The wind direction distributions represent the direction of the peak wind speed (peak wind direction) for a given event, but do not model the temporal variation of wind direction within an event. This simplification can be mitigated somewhat by the way the method is applied. The wind direction distributions (η in Equation 8-7, represented as PMFs) can be applied to give the probability of wind events with peak wind speeds occurring over a range of directions. These distributions represent the variability of the peak wind direction from the mean wind direction at the wind stations.

These distributions can also be used to represent the variability of wind direction at other locations near the stations. In this case, the distributions can be applied to the local mean wind direction at another location, as estimated from the mean spatial wind direction patterns (*h* in Equation 8-7). Additionally, the directional variability of winds and wind waves can be addressed using directional spreading functions (e.g., see Goda [1985]). An alternative simplified approach is to select the direction corresponding with the longest fetch for a given location and meteorology if, for example, that wind-wave direction might produce the greatest erosion.

The Pacific Low meteorology includes both southeasterly winds (typically pre-frontal winds) and westerly winds (typically following passage of a cold front). Hence, to represent both wind conditions, wind speeds for Pacific Low events should be considered for two wind directions. For Pacific Low wind events, the duration of the wind event, discussed below, can be split between the direction of the prefrontal wind speed and the direction of subsequent winds from the southwest to west. A reasonable assumption is that winds are southeasterly for half the duration and westerly for half the duration.

Wind duration distribution. Observational data can be used to determine a PMF of wind event duration for different meteorological types, which can be expressed as:

$$P(S(\underline{x}), d \mid m_i) \quad (8\text{-}8)$$

where

d = wind speed duration above a given threshold (in hours) for a given wind event.

Although the analysis of wind event duration showed that wind speed and wind event duration may be partially correlated, wind event duration was characterized independently of wind speed as a simplifying assumption. The simplified PMF of wind event duration can then be denoted:

$$P(d \mid m_i) \quad (8\text{-}9)$$

Timing of an event within a year. The timing of a wind event (for a given meteorology) within a year can be denoted by a PMF:

$$P(t \mid m_i) \quad (8\text{-}10)$$

where

t = the month of occurrence of a wind event

Probability of wind events. The probability of wind events can be determined from a combination of the various elements identified above. The probability of winds generally in the Delta and Suisun Marsh for events of a given meteorology can be expressed as follows:

$$P(S(\underline{x}) > s(\underline{x}), \theta(\underline{x}), d, t \mid m_i) = P(S(\underline{x}) > s(\underline{x}) \mid m_i)\, P(\theta(\underline{x}) \mid m_i)\, P(d \mid m_i)\, P(t \mid m_i) \qquad (8\text{-}11)$$

Uncertainty. Given that epistemic uncertainty exists in the elements of the model, uncertainty exists in the estimate of the probability of wind events, (S(x), θ(x), d). Based on an analysis of these uncertainties and propagating them through the analysis, the uncertainty can be denoted:

$$\{P(S(x) > s(x), \theta(x), d|m_i)_j, p_j\} \qquad (8\text{-}12)$$

where

p_j = the probability weight associated with the jth wind model

The model was implemented by sorting data for high wind events by wind meteorology, fitting extreme value probability distributions to the reference wind speed data, developing spatial wind patterns and distributions, and developing empirical probability distributions of wind event duration and month of occurrence.

8.3.2 Wind Characterization

As identified previously, three meteorologies cause winds with relatively consistent seasonal and directional patterns. The following meteorologies were identified:

- Pacific Low
- Polar Front
- Sea Breeze

The meteorology classification of each peak annual event was checked against wind speed and direction patterns at Travis, Sacramento, and Stockton and the time of year of each event. For events in which this information did not conform to the general pattern for the meteorology, synoptic charts were checked to confirm or re-classify the event meteorology. The peak wind speed and direction for certain events appeared to be erroneous. These wind events were not included in the extreme wind data sets, as a quality control measure.

The time series of wind directions and wind event duration for Pacific Lows are complex. Wind directions during Pacific Low events may shift from southeast to west at a given location as the storm front moves through the region. During Pacific Low wind events, high wind speeds typically occur for a duration of about 12 hours. A Pacific Low storm system may have multiple storm fronts or may be a series of storms. Thus, these 12-hour wind events may be preceded or followed by wind events of similar duration in which the peak wind speed is less. Analyzing the time series of wind events and series of multiple events was not evaluated in this study.

Wind data were characterized by the following parameters:

Reference Wind Speed Distribution

Travis was selected as the reference wind station because it has the longest data record and the wind speed at Travis is often the highest during high wind events (i.e., winds speeds at Travis are higher than at other stations for more than 80 percent of the peak annual wind events from 60 years of data record). As the spatial wind speed patterns are normalized, any station could be chosen as the reference station, and the results are not expected to vary significantly according to the station selection.

Two different probability distributions were tested for the reference wind speed:

1. Gumbel (Extreme Value Type I) Distribution
2. Generalized Extreme Value Distribution (GEV)

The distributions were fit to annual maximum wind speed data for each meteorology. Figure 8-2 shows the results for the GEV distribution for the three meteorologies.

Spatial Wind Distribution

The WOCSS model was tested as a method for spatially interpolating wind speed and direction for this study. Triangulation was selected as a wind speed interpolation method over the WOCSS model. The WOCSS model results were used to interpolate wind direction patterns and develop a spatial wind direction pattern.

The WOCSS model interpolates wind speed and direction in space using an inverse distance interpolation scheme between data points (wind stations) and imposes physical constraints on the interpolation to account for the effects of topography and atmospheric layering (Ludwig et al. 1991; Ludwig and Sinton 1998). The physical principles of the WOCSS model are intended primarily to account for complex physical terrain and atmospheric stratification. The physical principles are based on a two-dimensional nondivergence constraint to force flow interaction with topography and atmospheric layers. The WOCSS model is not an atmospheric model and does not solve differential equations for the conservation of momentum.

Figure 8-3 shows the mean and standard deviation of the wind spatial distribution model for the three meteorologies.

Spatial Wind Speed Distribution

Wind speed exceedance probability distributions were developed at selected locations throughout the Delta and Suisun Marsh region using normalized spatial wind speed patterns, applying these patterns to scale the reference wind speed distributions in space, and accounting for the variability in the spatial wind speed patterns.

Spatial Wind Direction Distribution

Wind direction exceedance probability distributions were developed at locations throughout the Delta and Suisun Marsh region using mean spatial wind direction patterns and PMFs of wind direction at each NWS station.

For each wind event modeled with WOCSS (9 hours modeled per event), the wind direction results were averaged to give a spatial map of wind direction for each event. For the five events modeled for each meteorology, the wind event direction maps were averaged to give mean spatial wind direction patterns for each meteorology. These results are shown in Figure 8-4.

Duration

The duration of wind speeds above 11 meters per second (m/s) were evaluated with respect to wind speed for the peak annual wind events from each meteorology. Wind event duration and wind speed appear to be partially correlated for Polar Fronts and Sea Breezes, but not for Pacific Lows. This difference could be explained by the fact that Polar Fronts and Sea Breezes may be characterized by meteorological conditions (i.e., pressure systems) that persist for more than a day, whereas Pacific Low storm systems may tend to move through the region within a day.

PMFs of wind event duration were calculated for each meteorology using wind data from the reference station (Travis), without consideration of wind speed. The duration PMFs are shown in Figure 8-5 for each meteorology. If the potential correlation with wind speed is not included as a simplifying assumption, the wind event duration PMFs could be applied to wind speed exceedance distributions at any location to give distributions of wind event duration and wind speed exceedance. This application may tend to underestimate the probability of longer duration events associated with higher wind speeds, and overestimate the probability of longer durations for lower, but more frequent wind speeds.

The wind event durations can be applied by assuming wind speeds increase from 11 m/s to the estimated peak wind speed, and then decreases back to 11 m/s over the event duration. For Pacific Lows, this assumption may not account for multiple storm fronts or a series of storm fronts, as the analysis approach only represents peak annual wind events and does not model stochastic processes involving multiple storms. Seasonal wind data include the full series of winds throughout the year. Additional discussion of the duration of Pacific Low events is included above.

Month of Occurrence

PMFs for the month of occurrence of peak annual wind events from each meteorology were calculated using wind data at the reference station (Travis). The PMFs for month of occurrence for each meteorology are given in Figure 8-6. The wind speed exceedance distributions (or other distributions) at a particular location can be multiplied by the probability of occurrence for a month to give the probability of a wind event (wind of a given speed) occurring during a given month.

Seasonal Winds

WRPLOT was used to create seasonal wind roses for the fall-winter season (October to March), spring-summer season (April to September), and the entire year for the period from 1997 to 2005 at each wind data station. The wind roses give the percent occurrence of wind speeds (from low to high) in eight compass directions. For other DRMS analyses using the seasonal wind rose data at a given location, the wind rose for the nearest NWS station can be used, as the NWS data are consistent and are expected to provide the most reliable data.

8.4 WIND-WAVE ANALYSIS

Wind-wave calculations were performed to develop look-up tables for wind-wave height and period, wave power, and wave runup. These look-up tables can be used to estimate deep-water wind-wave heights and periods, power, and runup for seasonal or extreme winds and any fetch of interest in other DRMS analyses.

8.4.1 Wind-Wave Generation

Wind-wave heights and periods were calculated for a range of fetch lengths and wind speeds using the procedures and parametric deepwater wave equations for fetch-limited wave growth from the Shore Protection Manual (USACE 1984).

Wind speeds estimated in the wind analysis are based on wind speed data measured over land (and are corrected to a 10-m wind gage height and 1-minute averaging period). The overland wind speeds were increased by a factor of 1.2 to estimate wind speeds over water, based on corrections provided in the CEM. The CEM recommends a correction factor of 1.2 for fetches less than 10 miles (16,000 meters). For longer fetches, the CEM gives this correction factor as a function of wind speed based on a Great Lakes study and provides additional correction factors for air-sea temperature difference and the stability of the atmospheric boundary layer. The factor of 1.2 was used for all fetches for consistency and simplicity.

For fetch-limited wave growth conditions in sheltered waters, the wind blows steadily in a constant direction for a sufficient amount of time to achieve steady-state fetch-limited wave conditions. Wind-wave generation requires a sustained input of wind energy. The adjusted 1-minute average wind speeds represent sustained winds with durations of 1 minute. The duration of the sustained wind speed that gives steady-state fetch-limited wave conditions may be longer (or shorter) than 1 minute. For each 1-minute wind speed estimate, wind speeds corresponding to a range of durations using Shore Protection Manual equations were calculated and these combinations of wind speed-duration were tested in the wave growth equations.

An automated computer code was used to find the wind-speed duration combination giving fetch limited conditions. The code calculates the duration for the highest wind speed-shortest wind duration combination to see if the calculated duration is sufficient to develop a fetch limited condition. If not, the code selects the next wind speed and repeats the calculation.

When the calculated duration for a given wind speed and fetch length is greater than the corresponding wind duration, the corresponding wind stress factor is used to calculate deep-water wave heights and periods, considered to be the largest fetch-limited condition. The results are included in tables found in Appendix A of the Wind-Wave Hazard TM (URS/JBA 2008g) for wind speeds above the highest estimated wind speed of interest (35 m/s, which has an exceedance probability of less than 0.002 for all meteorologies and fetch lengths beyond the longest fetch length, 21 km from east to west across Suisun Marsh).

8.4.2 Wave Power

Wave power is a measure of the rate of wave energy transmitted to a surface, such as a coastal structure or levee. As defined in the CEM, wave power refers to “the average wave energy flux per unit wave crest width transmitted across a vertical plane perpendicular to the direction of wave advance." Wave power is an indicator of potential work done toward levee erosion and generally provides an indication of intensity. Given that waves are dissipated over time and space, the actual work done on a surface depends on the shape of that surface and hence the antecedent wave conditions. Erosion is affected by the sequence of wave power, water levels, and event duration, and is more accurately modeled in terms of a time series of waves and erosion.

8.4.3 Wave Runup

Potential wave runup height is the height above the still water level that a wave breaking on a structure slope will reach as it travels up the slope, assuming the slope extends above the runup height. The actual wave runup height or elevation depends on the water level and structure crest elevation, which may limit runup height. However, potential wave runup is an indicator of water velocity on the structure slope, wave overtopping of the structure, and the potential for erosion of both the outboard levee slope and inboard levee slope (due to wave overtopping and head-cutting).

For each combination of wave height and period in the wind-wave generation look-up table, potential wave runup heights were calculated using the TAW method (2002) as described in the *Guidelines for Coastal Flood Hazard Analysis and Mapping for the Pacific Coast of the United States* (FEMA 2005a).

The TAW method and other wave runup methods give the wave runup height that is exceeded 2 percent of the time during a given wave event. This 2 percent wave runup height was calculated for each wind-wave height and period. The 2 percent wave runup height is otherwise not related to the probability of a given wind speed or wind-wave condition. Wave runup height calculated from the TAW method includes the super-elevation of the still water level due to wave setup (static and dynamic) caused by the wave conditions input into the equation. Note that in real situations, larger waves can break farther offshore of the slope and induce greater setup, which can in turn increase the local wave height and wave runup height elevation. The analysis accomplished here assumes the hindcast wave impinges on the slope and the wave runup includes all wave setup.

Wave runup heights were calculated for two structure slopes:

- 1 vertical to 1.5 horizontal (1:1.5) to represent relatively steep upper slopes of outboard and inboard levees that typically result in relatively high wave runup heights
- 1 vertical on 5 horizontal (1:5) to represent less steep lower slopes or average (composite) slopes of inboard levees

The TAW method includes wave runup reduction factors for surface roughness, the influence of a berm, oblique wave incidence, and structure permeability. FEMA (2005a) and TAW (2002) provide guidance on estimating wave runup reduction factors. These reduction factors were not included in wave runup calculations, and assumed smooth levee surfaces, the absence of a berm, perpendicular wave attack, and an impermeable structure (i.e., all reduction factors equal to one). For armored levees, a roughness reduction factor of 0.55 to 0.6 can be applied for levees with one layer of rock armoring, where the rock diameter (D) is one to three times the significant wave height ($H_s / D = 1$ to 3) (FEMA 2005a).

Table 8-1 Summary of Delta and Suisun Bay Wind Data

Agency	Data Type/QC	Station	Years of Record
NOAA/NWS	Wind Speed & Direction (daily)	Concord Buchanan	1973-2006
		Concord	1973-2006
		Livermore	1978-2006
		Sacramento	1948 - 2006
		Stockton	1941-1946, 1948-1955, 1963-2006
		Travis	1943-1970, 1973-2006
		Oakland	1943 only
NOAA NDBC	Wind Speed, Direction & Gust (hourly)	Port Chicago	1994-present
DWR	Wind Direction & Velocity	Antioch	1983 - 2006
		Mallard	1984 - 2006
		Martinez	1983 - 2006
		Rio Vista	1983 - 2006
CIMIS	Wind Speed & Direction (hourly)	Dixon	1994-2006
		Hastings	1995-2006
		Lodi	2000-2006
		Twitchell	1997-2006

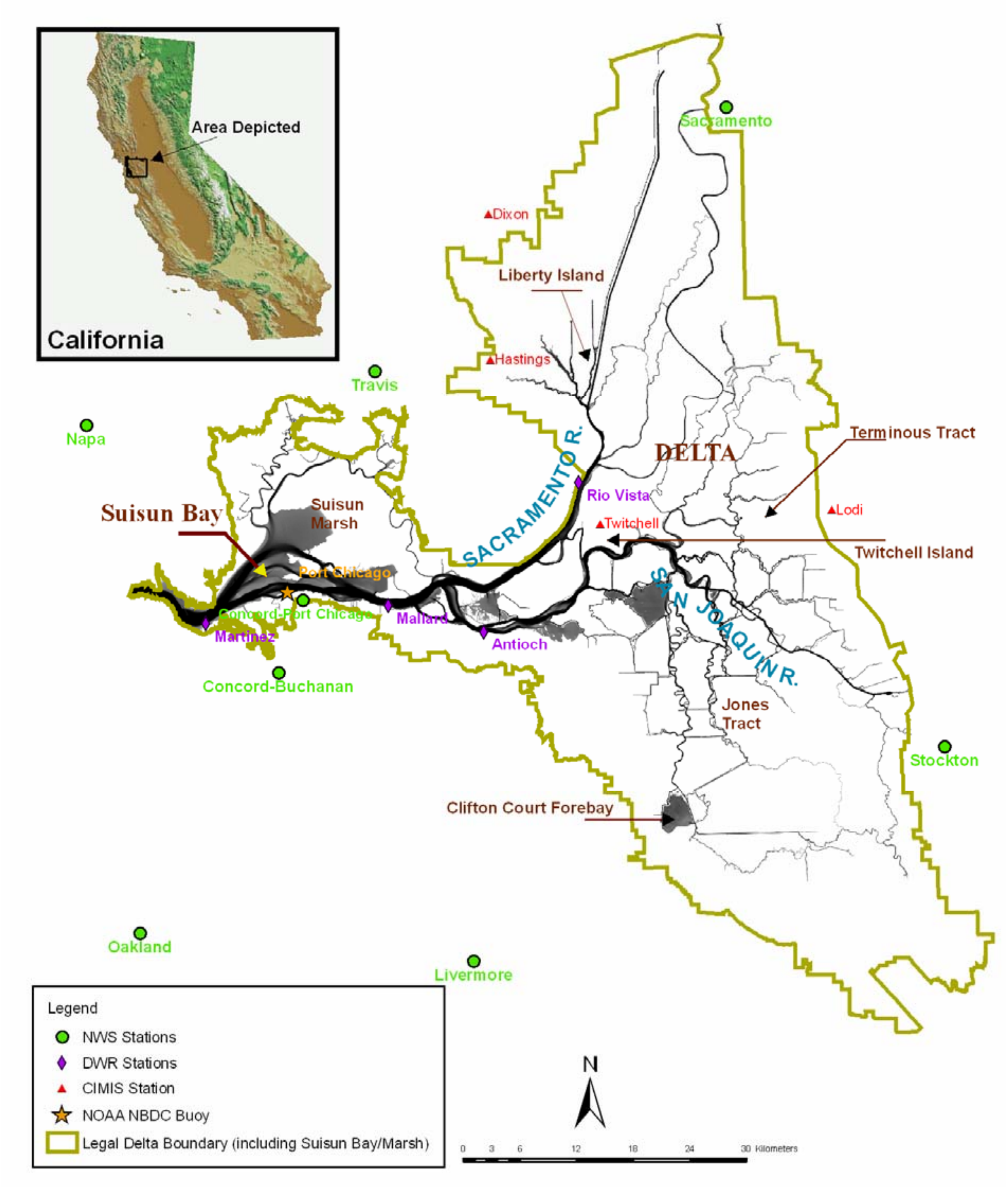

Figure 8-1 Site Map Wind Stations

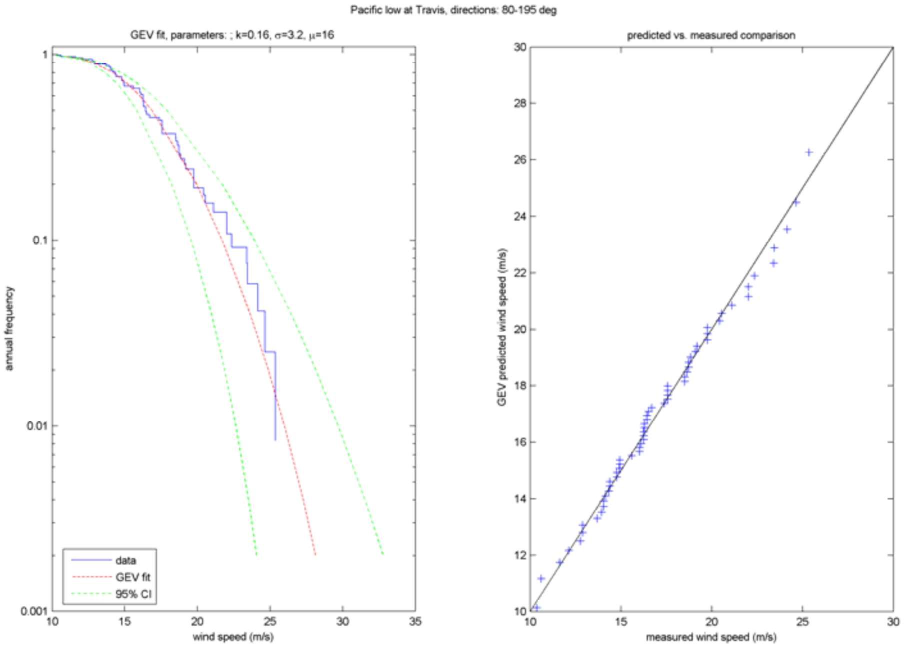

Figure 8-2a Wind Speed Distributions for Travis for Pacific Lows

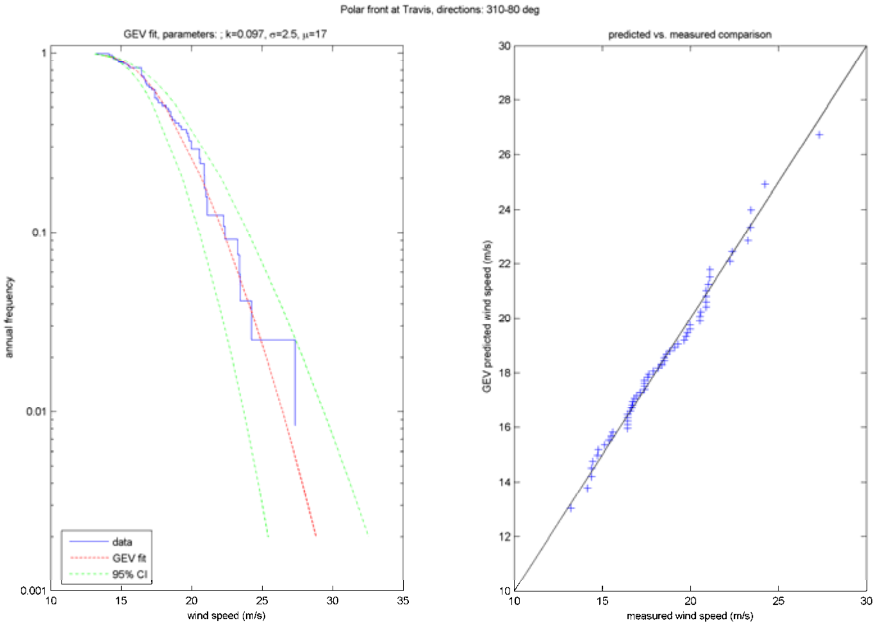

Figure 8-2b Wind Speed Distributions for Travis for Polar Fronts

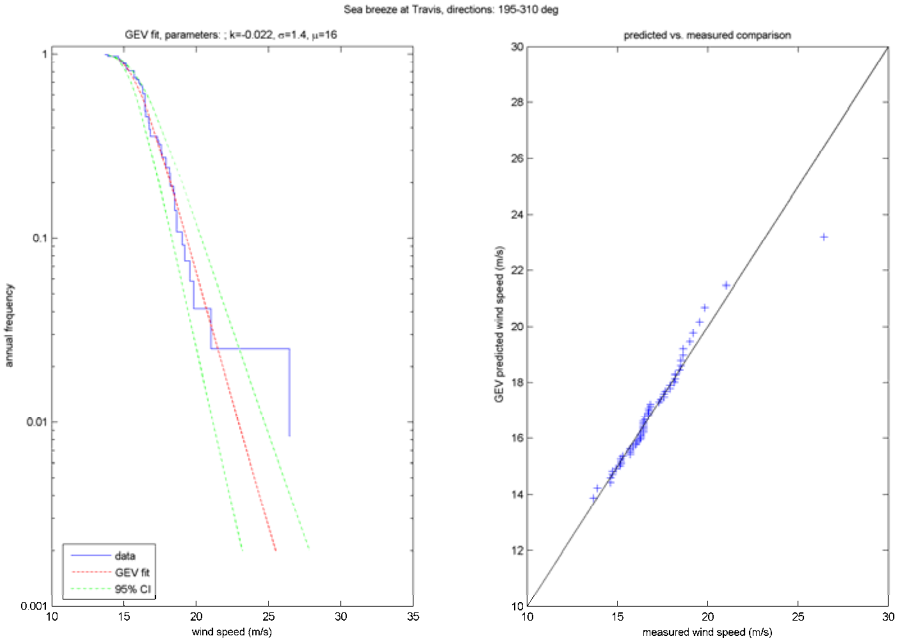

Figure 8-2c Wind Speed Distributions for Travis for Sea Breezes

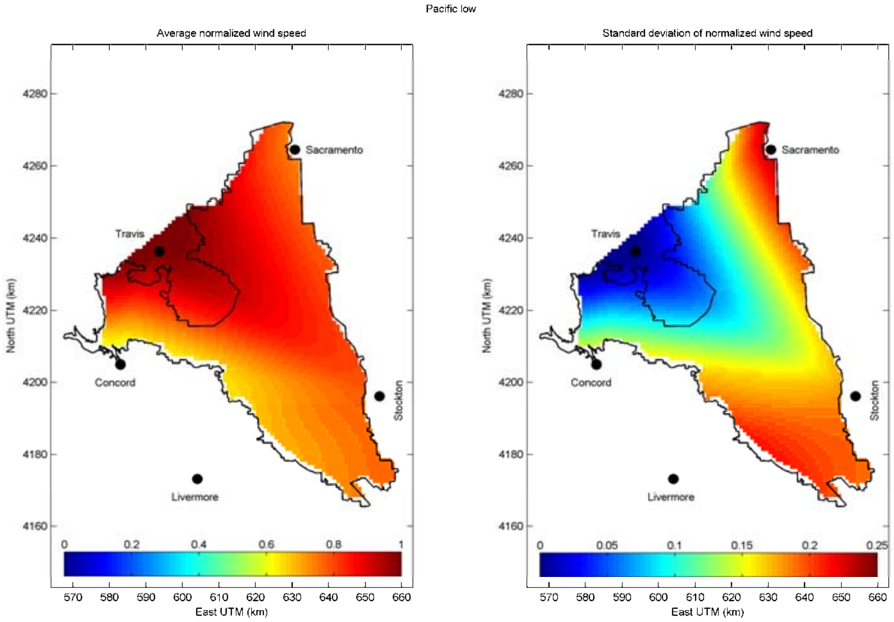

Figure 8-3a Spatial Wind Pattern, Mean and Standard Deviation for Pacific Lows

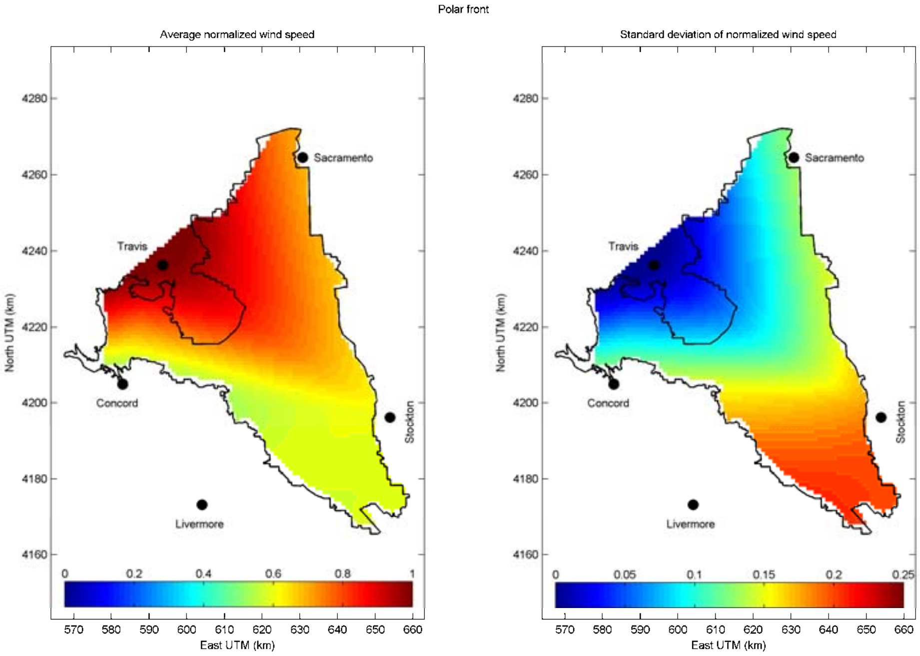

Figure 8-3b Spatial Wind Pattern, Mean and Standard Deviation for Polar Fronts

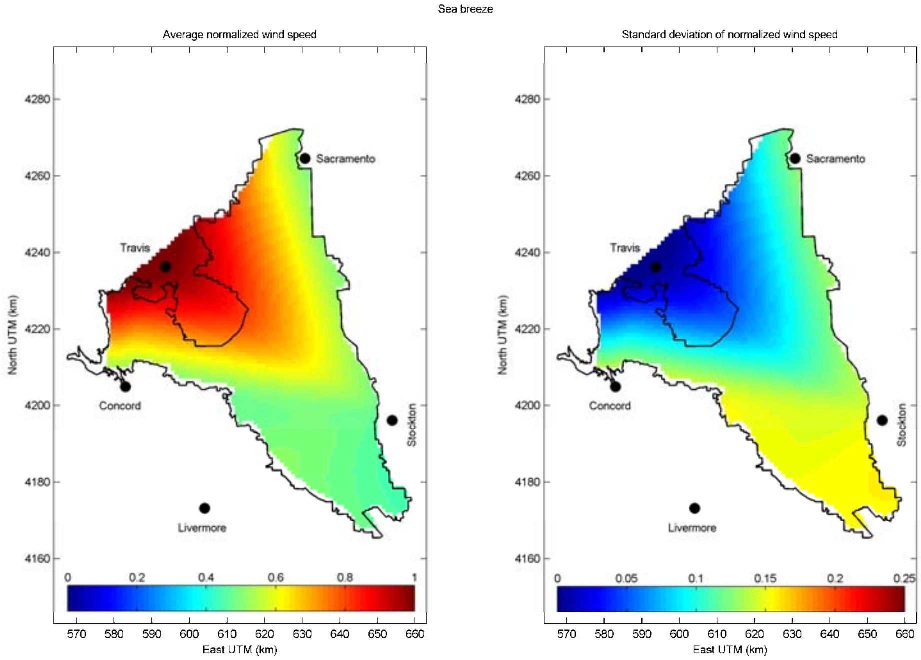

Figure 8-3c Spatial Wind Pattern, Mean and Standard Deviation for Sea Breezes

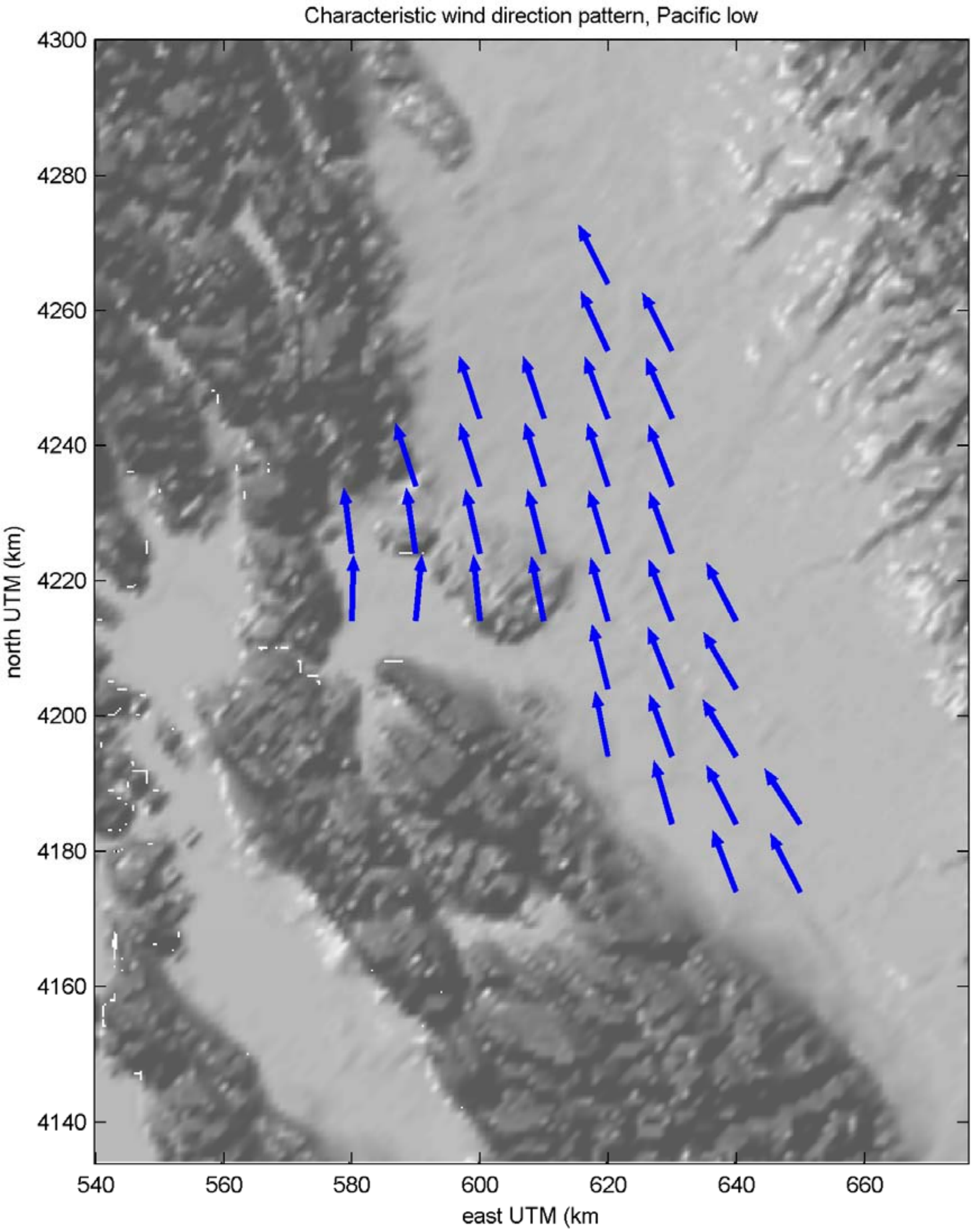

Figure 8-4a Spatial Mean Wind Direction Patterns for Pacific Lows

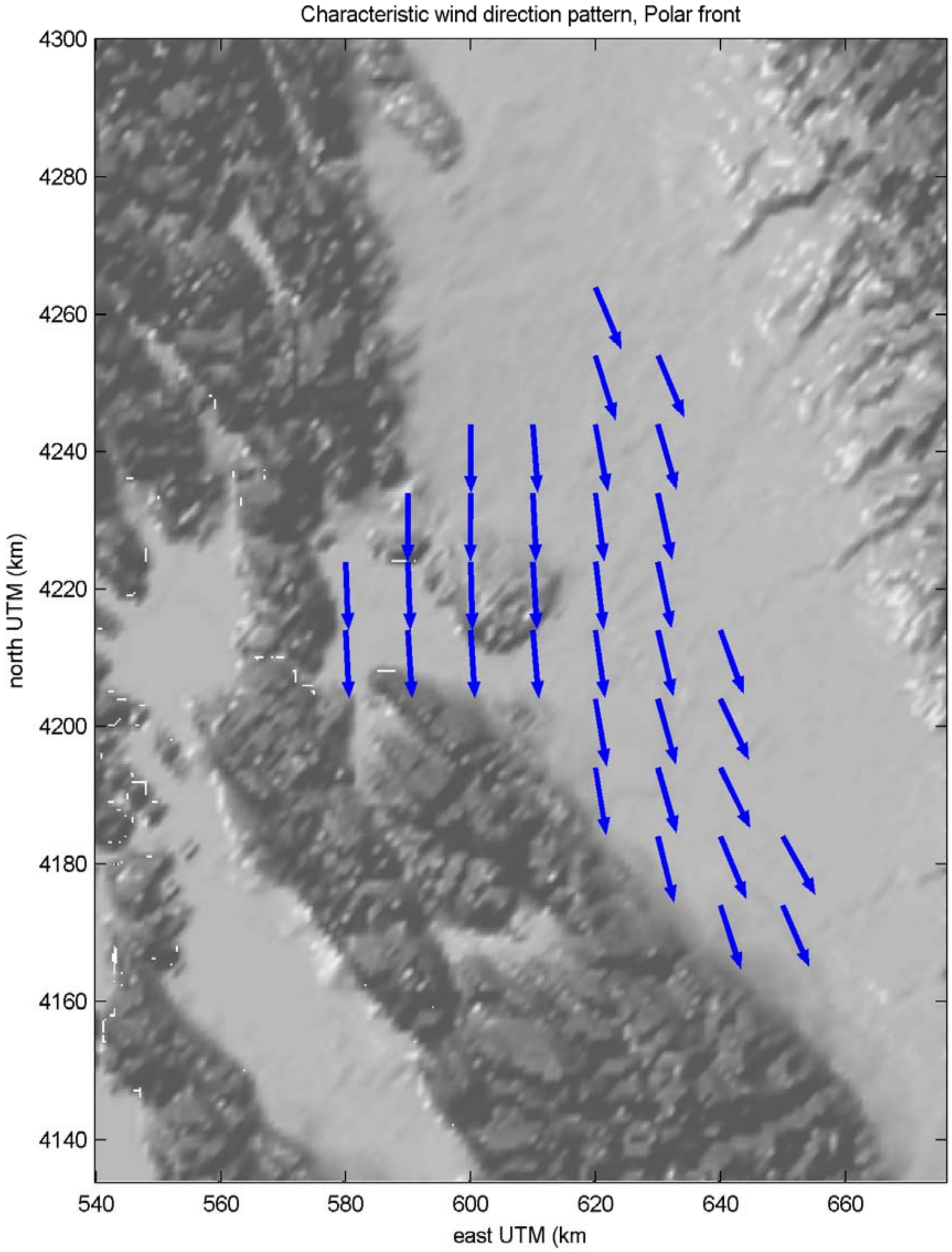

Figure 8-4b Spatial Mean Wind Direction Patterns for Polar Fronts

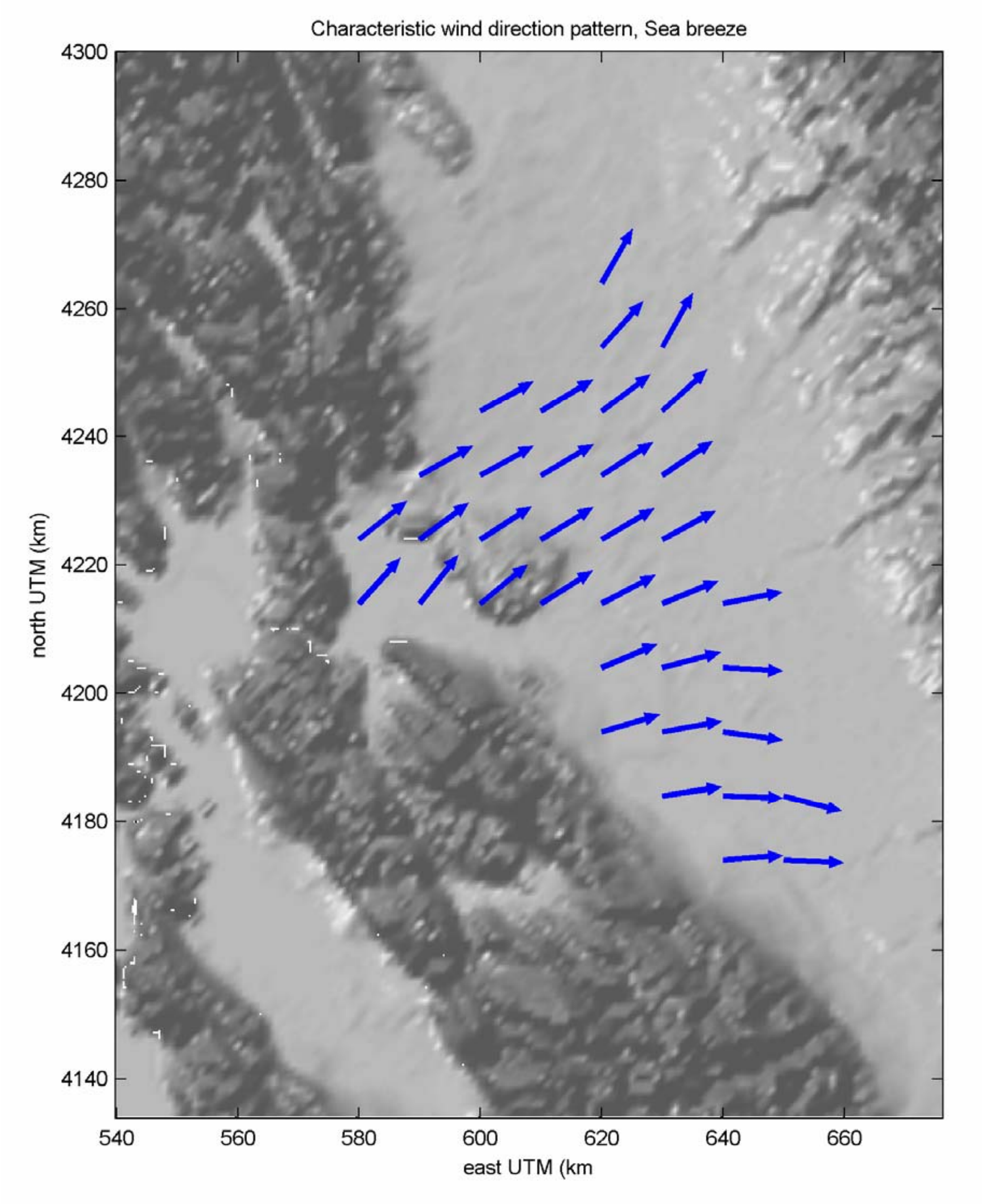

Figure 8-4c Spatial Mean Wind Direction Patterns for Sea Breezes

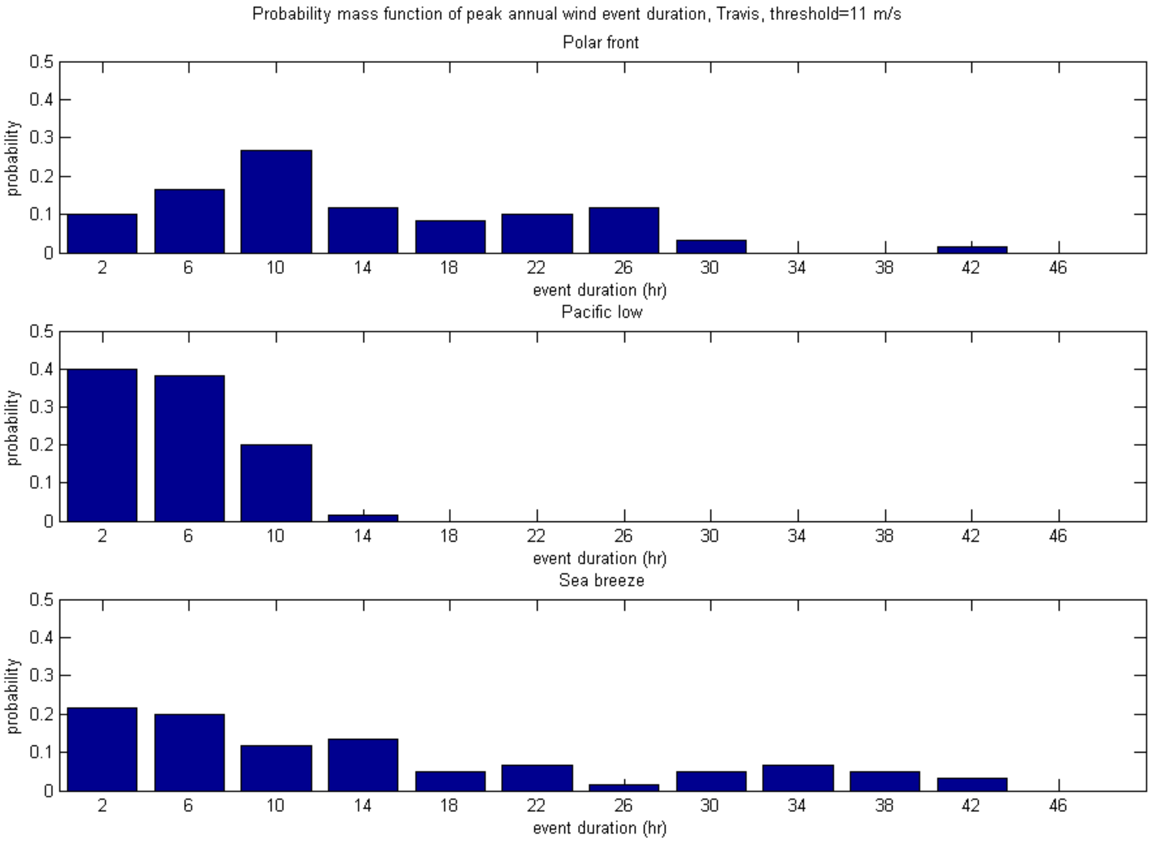

Figure 8-5 Wind Speed Duration for Each Meteorology

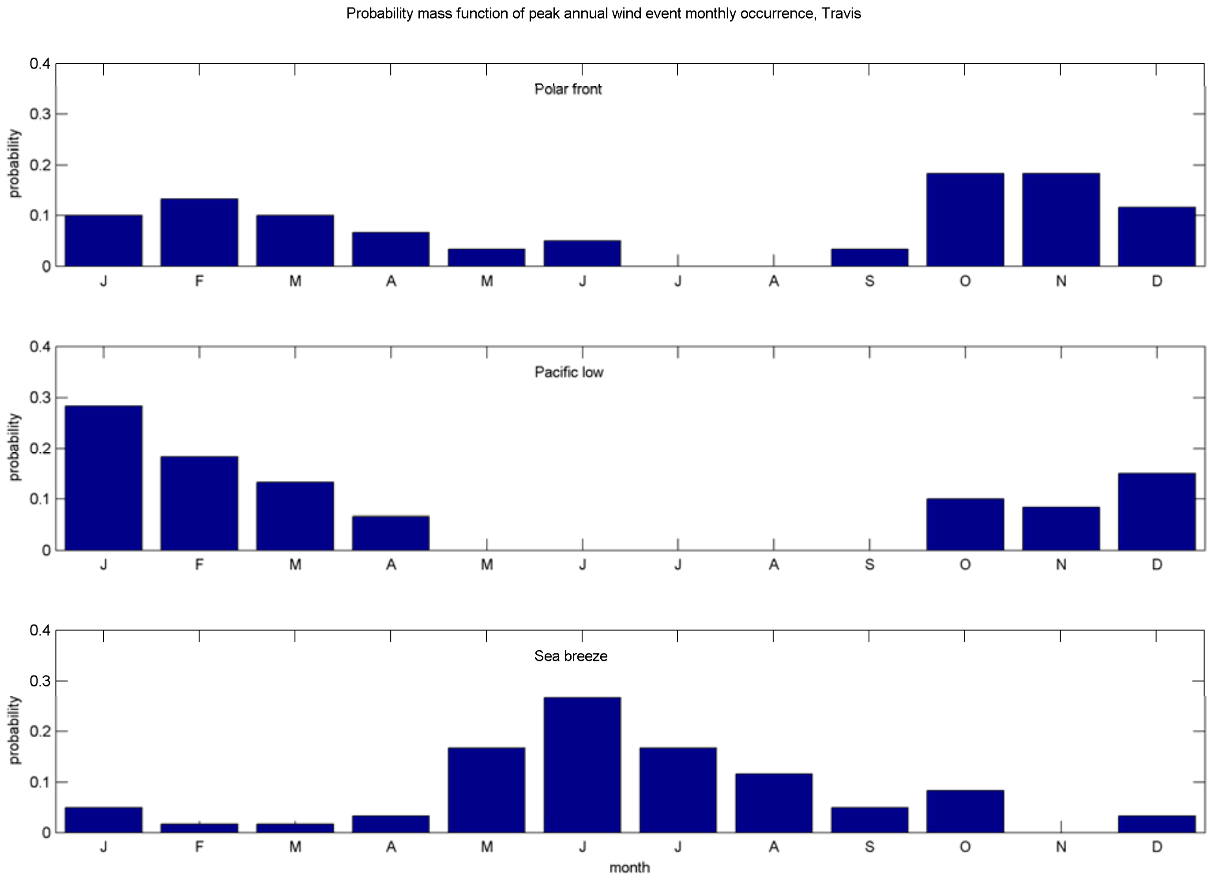

Figure 8-6 Probability Mass Function for the Month of Occurrence of Winds Associated with Each Meteorology Type